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The work by Professor Bekefi and his collaborators is summarized here

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Microwigglers for Submillimeter Wavelength Free Electron Lasers

Project Period 2-1-89 to 9-30-90

Prepared by George Bekefi
November 19, 1990

Massachusetts Institute of Technology
Research Laboratory of Electronics
Cambridge, MA 02139

Summary of Results

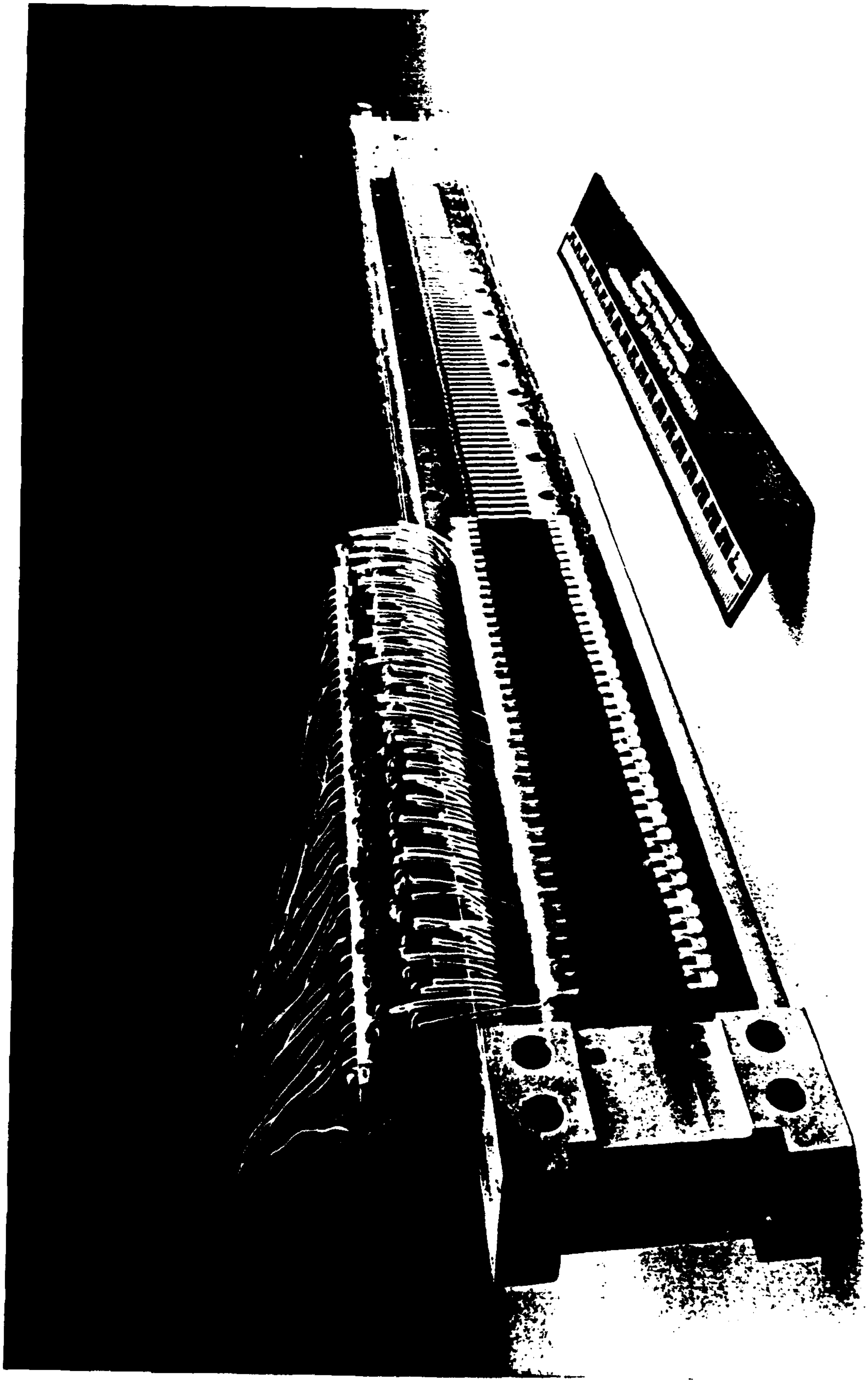
(a) The MIT microwiggler prototype produced on-axis magnetic fields of nearly 5 kG. Tuning was used to reduce random and systematic wiggler errors to $\lesssim 0.5\%$. Temperature measurements show that 0.5 msec, 5 kG pulses can be produced at 1 Hz at an operating temperature of 40°C above room temperature. lambda

(b) We are collaborating with the Brookhaven National Laboratory to develop a λ = 532 nm FEL using a 70-period microwiggler and a 50 MeV RF LINAC. Preliminary simulations show that oscillator operation is attainable.

(c) We have made preliminary measurements of a 20-period subsection of the MIT microwiggler. Saturation characteristics are acceptable and field uniformity without tuning is around 1% RMS.

The enclosed photograph shows the partially assembled microwiggler whose completed length will consist of 70 periods. (KH)

(d) The Appendix contains a reprint of our most recent paper together with a copy of a poster presented at the APS Conference in Cincinnati, Nov. 1990.



APPENDIX

A Planar Electromagnet Microwiggler For Free Electron Lasers

RICHARD STONER, SHIEN CHI CHEN, AND GEORGE BEKEFI

Abstract—We have designed and tested an electromagnet planar microwiggler for use in free electron lasers (FEL's), constructed of current conductors wound on ferromagnetic cores. A prototype with a period of 1 cm and gap of 0.5 cm produced a peak field on axis in excess of 4.6 kG, with a linear B/H characteristic to about 3.2 kG. The field of each half-period of the wiggler is independently tunable by adjusting the current delivered to each, thus allowing for precision tuning and/or wiggler tapering. We employ general scaling laws to predict the performance of a geometrically similar design with a period of 5 mm.

I. Introduction

Short-period (1-10 mm) wigglers for free electron laser (FEL) applications have been a subject of considerable interest [1]-[6]. The use of such a microwiggler permits higher frequency radiation to be generated with a device which is more compact than one employing wigglers of standard lengths (typically 3-10 cm).

Reduced length scales imply that fabrication imperfections become increasingly more serious. Field amplitude tunability, as a means of compensating for the resulting random field errors, becomes a particularly important attribute for a microwiggler design. Field amplitude tunability also has a general usefulness for applications like field tapering for FEL efficiency enhancement. The use of electromagnets permits such tunability; moreover, a planar geometry wiggler readily lends itself to a tunable configuration inasmuch as it can be made of discrete electromagnets.

This paper describes a new planar electromagnet microwiggler design and the measurements of its performance. The work is an outgrowth of earlier studies [6]. Section II presents experimental results; Section III discusses the design of our new prototype test piece and uses general scaling laws to predict the performance of geometrically similar designs at reduced length scales. It is shown that the attainable time-averaged value of the magnetic field in pulsed-mode operation remains constant as the size is decreased.

II. Experimental Results

We have constructed a four-period microwiggler prototype with a period of 10.2 mm and gap of 5.1 mm consisting of 16 wire-coil electromagnets wound on laminated Microsil (silicon-iron) cores. Each core consists of seven laminations of dimensions $1.27 \times 3.81 \times 0.0356$ cm. Fig. 1 illustrates the geometry. The test piece has a tunable amplitude with the current delivered to each half-period, adjustable by means of a precision potentiometer. Each coil consists of 50 turns of 32 AWG copper wire (0.0202 cm diam.) and has a resistance of 2.4 Ω. The coils are connected in parallel and the wiggler is energized by a simple pulser circuit consisting of an air-core inductor ($L = 1.3$ mH) and a bank of six 1500 μF capacitors connected in parallel. The resulting waveform is an underdamped sine wave. The pulser is fired by an SCR which commutates off at the first zero crossing of the current. Hence the wiggler is energized by a single positive current pulse. The full period of the underdamped waveform is about 22 ms.

The wiggler field amplitude as a function of the input current density was measured and is shown plotted in Fig. 2. The results of a Poisson simulation are seen to match the data quite well—this is partly fortuitous, since we made no effort to model the permeability of our particular material. The probe was located at a peak near the central part of the wiggler; the input current was measured using a Rogowski coil and the field was measured by means of a Hall probe gaussmeter, using a specially designed miniature probing tip. The current values shown are those borne by the 32 AWG wire: A current of 20 A corresponds to a current density of 6.24×10^4 A/cm^2.

Note that B as a function of I is quite linear to about 3.2 kG. The 3-kG linear field regime of our design extends further than those of ferro-core designs reported previously [1], [2], [6]. Fig. 3 shows a Poisson-generated flux map of our prototype in its linear B/I regime. The regions of highest flux density in the cores occur inside the windings, which are thus purposely displaced toward the polefaces relative to the center of the cores. The closer to the polefaces the highest flux density region occurs, the higher will be the fields at the polefaces (and on the wiggler axis) when the cores saturate. The windings do not extend along the entire ferro-core since in such a configuration the highest flux density occurs at the center of the cores, well back from the polefaces, leading to the onset of saturation at relatively low field levels.

Fig. 4 shows the prototype's measured, untuned, on-axis magnetic field profile. Poisson calculations of the peak fields are also shown. There is very little higher harmonic content in the field. This is mainly due to the large

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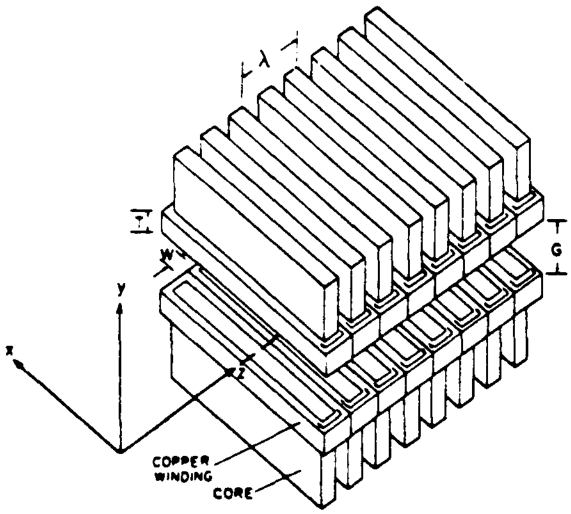

Fig. 1. Geometry of the microwiggler test piece. The coordinate axes as well as definitions of design parameters are shown. The arrows inscribed on the copper windings indicate the direction of current flow.

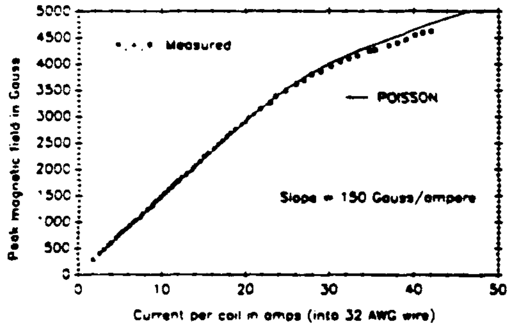

Fig. 2. Wiggler field amplitude as a function of current density. Measured data and Poisson calculations are shown.

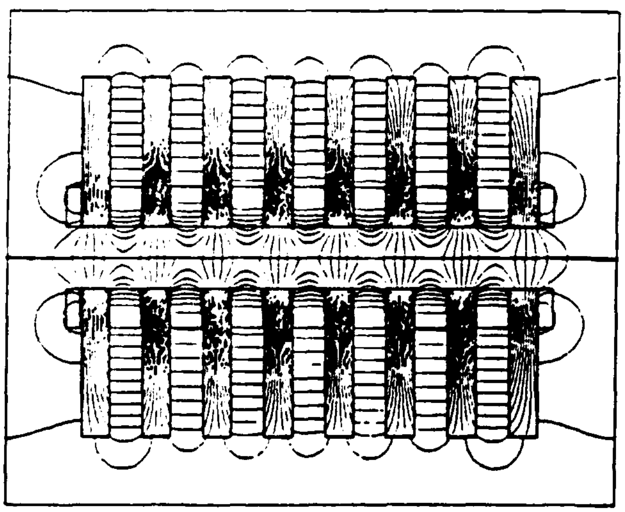

Fig. 3. Poisson-generated equipotential map for the MIT prototype. The field map shown corresponds to the linear B/H regime.

gap-to-period ratio: The field at a given point on the wiggler axis is the sum of contributions from many half-period elements. The wiggler end effects are quite small

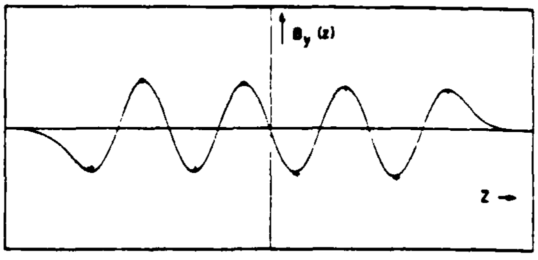

Fig. 4. Measured wiggler field profile taken along the wiggler (z) axis without tuning. The continuous curve is the measured data. Poisson-calculated values for the peaks are shown as crosses.

due to the favorable symmetry of the current density about the central plane perpendicular to the wiggler (z) axis, as will be mentioned in Section III. In the absence of tuning we observe random field amplitude errors in the prototype of $\pm 4\%$; this is a reasonable value, considering the very simple methods used in its construction.

Random field errors as well as undesired systematic finite wiggler effects are sharply reduced by tuning. The results of profile tuning experiments are shown in Fig. 5. Fig. 5(a) is a plot of the prototype's on-axis magnetic field tuned to a constant-amplitude profile. Random field errors are 0.4% rms, with a maximum deviation from the constant amplitude of 0.6%. Amplitude tuning has therefore reduced random field errors by an order of magnitude. Minor improvements in the tuning regimen should permit further reduction of random errors, perhaps to the level of 0.2% rms. Fig. 5(b) is a measured profile demonstrating the capability of adiabatic field up-taper for improved e-beam coupling into the wiggler. The magnet was dc energized with about 0.5 A per coil (for a total of 8.0 A) during the tuning and profile measurements.

Fig. 6 is a plot of the measured wiggler field profile across the gap, along a line from poleface center to poleface center. The data are again well-matched by the Poisson code (using its standard permeability table) and also well-represented by a hyperbolic cosine curve, in agreement with expectations. The distance over which measurements could be taken was restricted by the Hall probe hitting the polefaces.

Heat generation, even under the pulsed conditions of the wiggler, is, of course, of major concern. A simple calculation shows that the I^2R heating induced by the underdamped waveform with maximum current I_{max} is equivalent to that induced by a square pulse of height I_{max} and duration of 5 ms. Even with this long pulse, the maximum peak field value shown in Fig. 4 (4.6 kG) is not the highest attainable field. At $I = 57$ A, $(I^2R \cdot 5$ ms) corresponds to a temperature increase of 80°C. We have found the Formvar insulation to be reliable to around 100°C –80°C above the typical ambient temperature of 20°C so that (from a rough extrapolation of the measurements of Fig. 4) 5-ms field pulses of 5 kG are clearly attainable. For a wiggler of 50 periods a 11.4-kA pulser is required in order to provide 57 A per coil, and, given the modest voltages involved (less than 0.5 kV), its construction poses no special difficulties. It is then reasonable

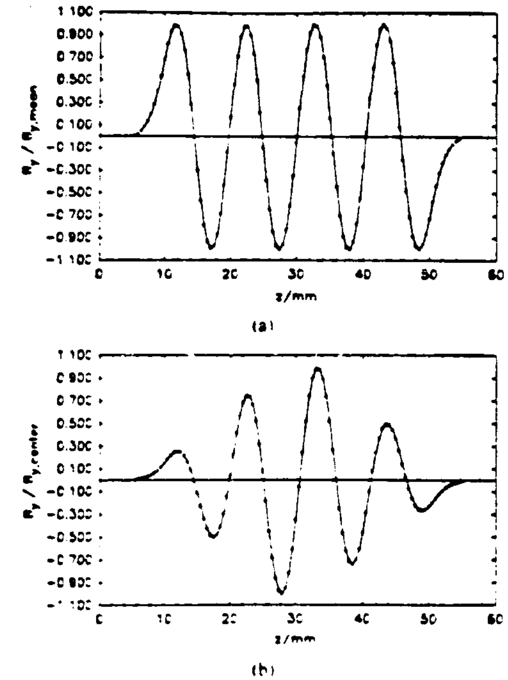

Fig. 5. Measured wiggler field profiles taken along the wiggler (z) axis, with tuning. A constant amplitude profile is shown in (a). The amplitude is constant to 0.47% rms with a maximum deviation of 0.6%. A "linear ramp" profile is shown in (b), which demonstrates the capability for adiabatic up-taper for wiggler e-beam matching.

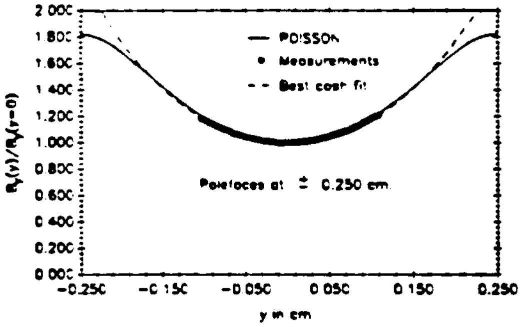

Fig. 6. Measured wiggler field profile taken across the wiggler gap from poleface center to poleface center. The data is normalized to the value of the field at the gap center. A Poisson calculation of the field profile is shown, as well as the hyperbolic cosine function that best fits the data.

to claim 5.0 kG as a practical maximum attainable field from a full 50-period wiggler in long-pulse operation. For short-pulse operation, higher fields could be attained, but current and voltage requirements become formidable as the ferro-cores saturate.

For an extremely short pulse duration and very high fields, a pulsed-wire geometry with no ferro-cores may well be preferable [7]. Nevertheless, the ferro-core design can produce a 3-kG square pulse of 40 ms duration, while a reasonable pulsed-wire design could produce such a pulse for only a fifth of that time. Using more exotic, high-μ materials could likely make attainable 3-kG pulses of 0.1-s duration in a magnet with gap-to-period ratio of 0.5.

III. Design Discussion

To aid us in our design, we began by leaving out the ferromagnetic cores. Fig. 7 illustrates an infinite two-dimensional array of parallel rectangular conductors carrying currents of identical magnitude in a configuration that produces a periodic magnetic field on the axis of the structure. Expressing the current density in terms of a Fourier transform permits the calculation of an exact analytical expression for the magnetic field: An expression for the field valid inside the wiggler gap (i.e., between the two planes of conductors) is

$$B_y = \frac{8j\lambda}{\pi c} \sum_{\substack{n>0 \\ \text{odd}}} \frac{1}{n^2} \sin\frac{n\pi}{2} \sin\frac{n\pi W}{\lambda} \left(1 - e^{-2\pi T/\lambda}\right) e^{-\pi G/\lambda} \cdot \cos\frac{2\pi z}{\lambda} \cosh\frac{2\pi y}{\lambda}$$

$$B_z = -\frac{8j\lambda}{\pi c} \sum_{\substack{n>0 \\ \text{odd}}} \frac{1}{n^2} \sin\frac{n\pi}{2} \sin\frac{n\pi W}{\lambda} \left(1 - e^{-2\pi T/\lambda}\right) e^{-\pi G/\lambda} \cdot \sin\frac{2\pi z}{\lambda} \sinh\frac{2\pi y}{\lambda}. \qquad (1)$$

Here c is the speed of light, j is the current density in the windings, G is the gap spacing, λ is the wiggler periodicity, T is the winding thickness in the y direction, and W is the winding thickness in the z direction, with $(\lambda - W)/2$ as the core thickness to be inserted (see Fig. 7). This result illustrates well-known general properties of planar wigglers: Exponential decrease in field magnitudes with increasing (G/λ) and the absence of even harmonics in the field. It is also interesting to note that (1) has precisely the same form as the expression for the magnetic field due to rare-earth cobalt (REC) magnets in the Halbach configuration [8] to an overall multiplicative constant (REC magnetization being analogous to electromagnet current), except that the REC magnetic field harmonics fall off as $1/n$ instead of $1/n^2$. Simulations reveal that a finite structure with a current distribution symmetric in z and having half-width conductors at the ends produces a field closely modeled by (1) at points more than a couple of periods in from the ends of the structure.

Equation (1) predicts that a pulsed-wire design with $\lambda = 1.0$ cm, $G = 0.5$ cm, $W = 0.211$ cm, and $T = 0.211$ cm (81 turns of 32 AWG wire per coil) will produce 68 G of magnetic field on axis per ampere of current. The addition of ferromagnetic cores substantially increases B/I efficiency, and in fact will produce 150 G/A as described in Section II. Improved field per unit input current density is not the only reason for including ferro-cores: The ferro-cores can be embedded in an external matrix formed with very high precision, thus precisely fixing the core positions. Inasmuch as fully two-thirds of the magnetic field in the linear B/H regime in our design is due to induced magnetization currents in the ferro-cores, there is great advantage in the field precision to be gained by locating them precisely. Moreover, cumulative field periodicity errors occurring in ferro-core/solid-conductor

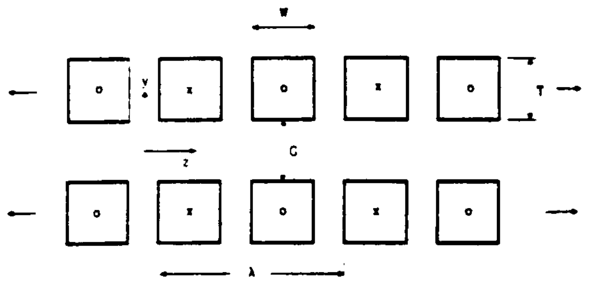

Fig. 7. Two-dimensional planar wiggler structure without ferro-cores. The coordinate axes and parameter definitions are shown. The structure is taken to be infinite in extent along the x direction (perpendicular to the page), and to be infinite and periodic along the z direction (wiggler axis). The conductors carry uniform currents of identical magnitude in the directions indicated. (x)—current into paper. (o)—current out of paper.

stack designs [2] are eliminated by embedding the cores in an external matrix, which can only be done if the ferro-cores extend beyond the conductors as in our design. Thus we see an additional advantage of placing the conductors at the polefaces and extending the cores beyond the conductors, in addition to the saturation advantage described in Section II.

The relative "width" along the z axis of the ferro-cores and wires was determined empirically by numerical simulations: The width with the best saturation characteristic was found, and then T was reduced to the point where the B/I efficiency in the linear regime was about 150 G/(A into 32 AWG coil wire). It was observed that increasing T for fixed wire diameter and ferro-core widths increased B/I efficiency but lowered the field value at which saturation occurred. The B/I efficiency grew roughly linearly with T, and the product of the efficiency and the saturation field was roughly constant.

We are also considering the construction of a 5-mm-period wiggler by using the geometry of our 10-mm-period prototype with all length factors reduced by a factor of two. Simple scaling laws can be used to predict the performance of geometrically similar designs (i.e., all lengths scaled by the same factor.) Equation (1) shows the peak field magnitude scales as

$$|\bar{B}| = j\lambda f(G/\lambda, T/\lambda, W/\lambda) \tag{2}$$

for the simple pulsed-wire design; it can easily be shown that a ferro-core system in its linear B/H regime has the same kind of scaling [9]. That is, the field magnitude scales like ($j \cdot \lambda \cdot$ function invariant under length scale). The 5-mm-period design then requires twice the current density to attain a given field level, compared to the 10-mm-period design. Therefore to maintain a given field amplitude and given conductor temperature increase per shot, field pulse durations must be reduced by a factor of four in the 5-mm-period design.

The saturation field of the 5-mm-period design is the same as that of the 10-mm-period design and the (L/R) rise time of the 5-mm-period structure (in the linear B/H regime) is one-fourth that of the 10-mm-period system. One can also prove that the characteristic conduction cooling time of the 5-mm-period structure is one-fourth that of the 10-mm-period design.

The factor-of-four reduction in the cooling time permits the 5-mm-period device to operate at four times the pulse repetition frequency of the 10-mm-period design, assuming a fixed temperature increase per pulse. This more-rapid pulsing rate is possible because the (L/R) rise time is four times smaller in the smaller structure, and so the time scale of the current waveform can be compressed. Reducing the duration of each pulse by a factor of four permits the doubling of the current density with no change in the temperature increase per pulse, so that the same $|\bar{B}|$ can be attained during the shorter pulse in the smaller structure. This implies that the smaller structure can produce magnetic field pulses of a given magnitude having one-fourth the pulse length at four times the rate—so that the time-averaged $|\bar{B}|$ attainable by the 10-mm-period design can also be generated by a 5-mm-period wiggler.

The wiggler parameter K (also called a_w) defined by [10]

$$K = \frac{eB_w \lambda_w}{2\pi mc^2} \tag{3}$$

figures prominently in efficiency enhancement schemes using wiggler tapering to maintain resonance as the electrons' energy is radiated and γ decreases [10]:

$$\lambda_{res} = \frac{\lambda_w(1 + (K^2/2))}{2\gamma^2}. \tag{4}$$

Our design permits high-precision wiggler amplitude down-tapering. It must be noted, however, that for periods much shorter than 1 cm, K becomes too small (e.g., $K = 0.23$ at $\lambda_w = 5$ mm) so that amplitude tapering is of dubious usefulness, since the "dynamic range" of K^2 is then very limited.

An important limitation of ferro-core electromagnet wigglers is that they are largely incompatible with externally applied magnetic fields; e.g., a quadrupole field for beam focusing. This limitation can be circumvented in part by employing two-plane wiggler focusing schemes in which the planar geometry is modified, such as poleface shaping or poleface canting [11], to obviate the need for external focusing.

IV. Conclusion

We have built a four-period microwiggler prototype with a 10.2-mm period and 5.1-mm gap, using a design which permitted the attainment of 3.2 kG on-axis peak magnetic fields in the linear B/H regime while preserving good B/I efficiency for generation of long (40 ms at 3 kG) magnetic field pulses. In this regime, fine tuning of the wiggler is readily achieved by varying the current in the individual elements. Fields exceeding 4.6 kG in the saturated B/H regime were observed. When precise tuning of the wiggler is not an issue, the operation in the saturated regime may well yield magnetic fields as high as 5 kG. A measured profile of the field taken along the

wiggler axis shows good agreement with numerical simulations. End effects are minimal. Tuning is shown to dramatically improve field uniformity, reducing random field errors by an order of magnitude from $\pm 4\%$ in the untuned profile to $\pm 0.4\%$ in the tuned case. A measured profile of the field taken across the wiggler gap also shows good agreement with computational predictions.

We have developed a simple design regimen for pulsed-wire planar wigglers based on analytic expressions for magnetic fields and L/R rise times which we used as a conceptual basis for our ferromagnetic core-based design. We have briefly discussed our design procedure and used general scaling laws to predict the performance of a geometrically similar design with a 5-mm period and 2.5-mm gap. We show that the smaller structure should be able to produce the same time-averaged magnetic field as the 10-mm period design in pulsed-mode operation.

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Richard Stoner was born on November 25, 1954 in Mason City, IA. He received the B.S. degree in physics from the University of Washington, Seattle, in 1981. After three years at TRW, Inc., Redondo Beach, CA, where he worked in radar signal processing and analysis, he resumed his studies at the Massachusetts Institute of Technology, Cambridge, where he is a Ph.D. degree candidate in physics, engaged in the development of a microwiggler-based, visible-wavelength free electron laser at the Brookhaven National Laboratory Accelerator Test Facility.

Shien Chi Chen was born in Taipei, Taiwan, on February 23, 1956. He received the B.S. degree in physics from National Taiwan University in 1978, and the Ph.D. degree in physics from Columbia University, New York, NY, in 1984.

From 1984 to 1986 he was engaged in research on far-infrared free electron laser and spectroscopy at AT&T Bell Laboratories, Murray Hill, NJ. He joined the Massachusetts Institute of Technology, Cambridge, in 1986 and has been engaged in research on high-power coherent radiation generation and applications.

George Bekefi, photograph and biography not available at the time of publication.

MIT MICROWIGGLER FEL PROJECT

R. Stoner, S.C. Chen, and G. Bekefi
Massachusetts Institute of Technology

- MICROWIGGLER – an FEL wiggler of period 1–10 mm

  Useful Attributes:

  - Compactness
  - High–frequency output radiation per unit input electron energy

- TUNABILITY – provides for:

  - Reduction of random amplitude fluctuations
  - Field amplitude tapering
  - Wiggler entrance e–beam matching

MIT MICROWIGGLER PROTOTYPE

- o Type: pulsed electromagnet with ferromagnetic cores; each half-period is independently tunable

- o Attributes:

  λ_w = 10.2 mm
  G = 5.1 mm
  4 periods
  $B_{max,observed}$ = 4.6 kG

- o Attainable rep-rate (0.5 msec, 5 kG pulses) > 1 Hz

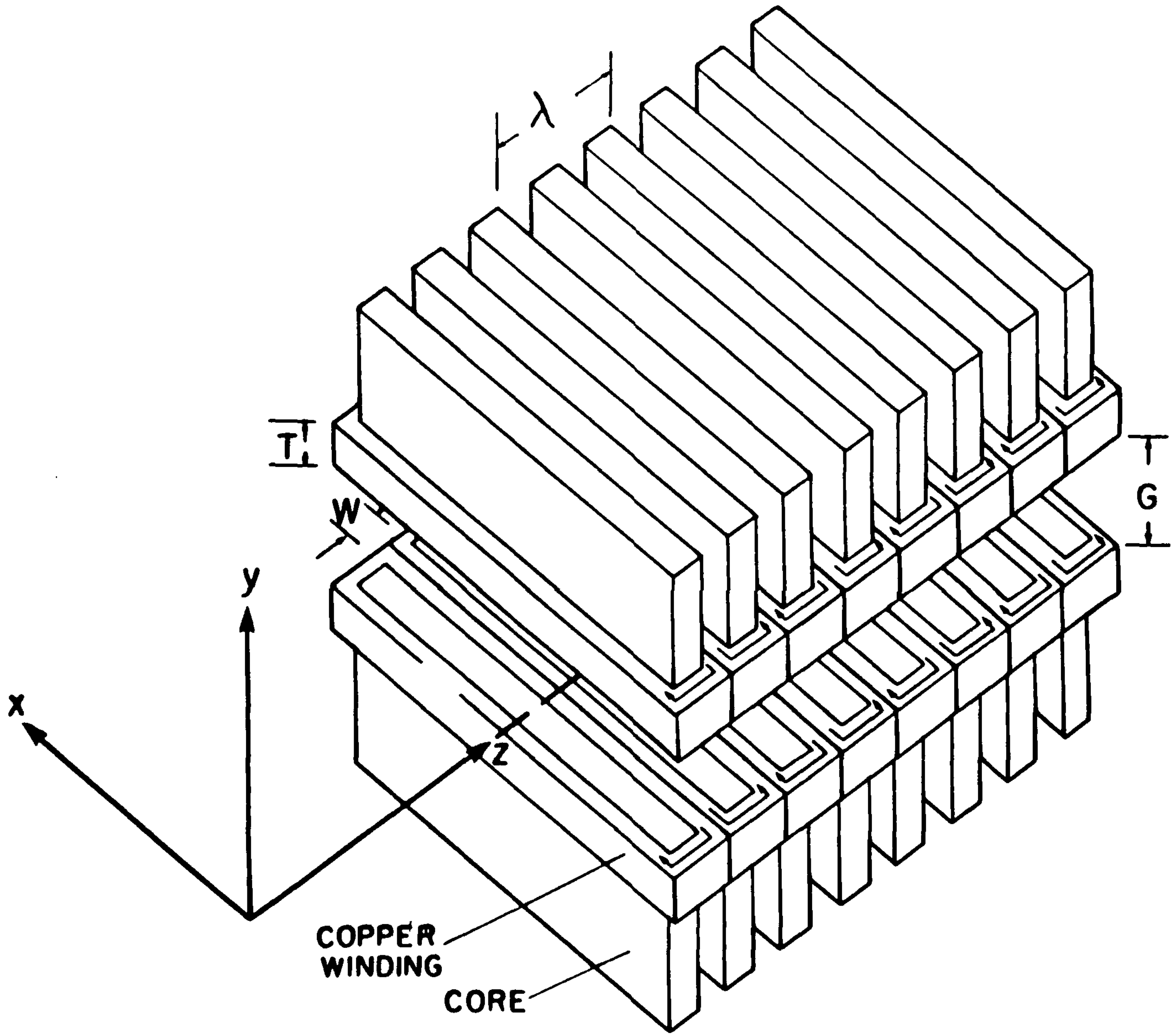
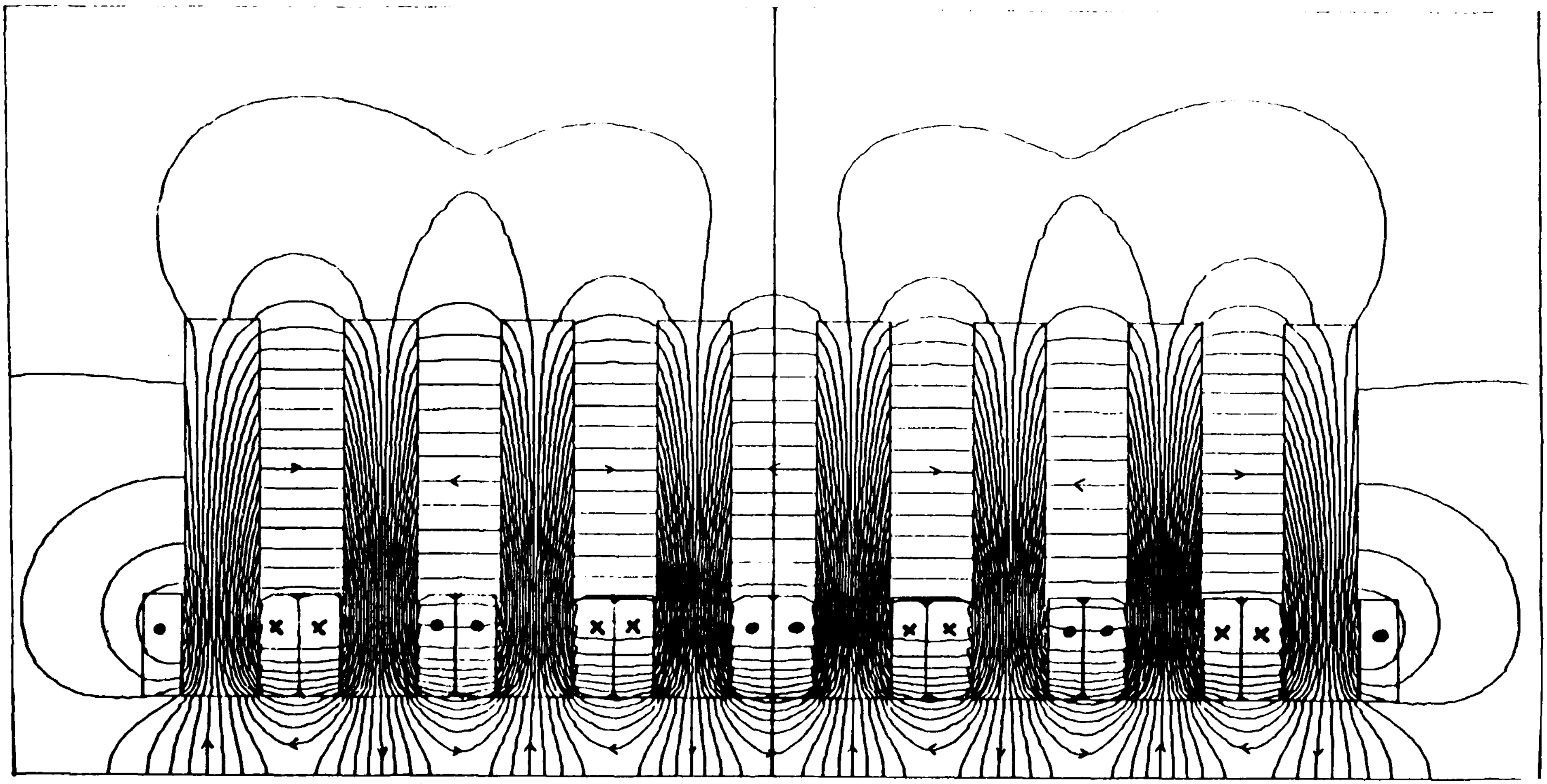


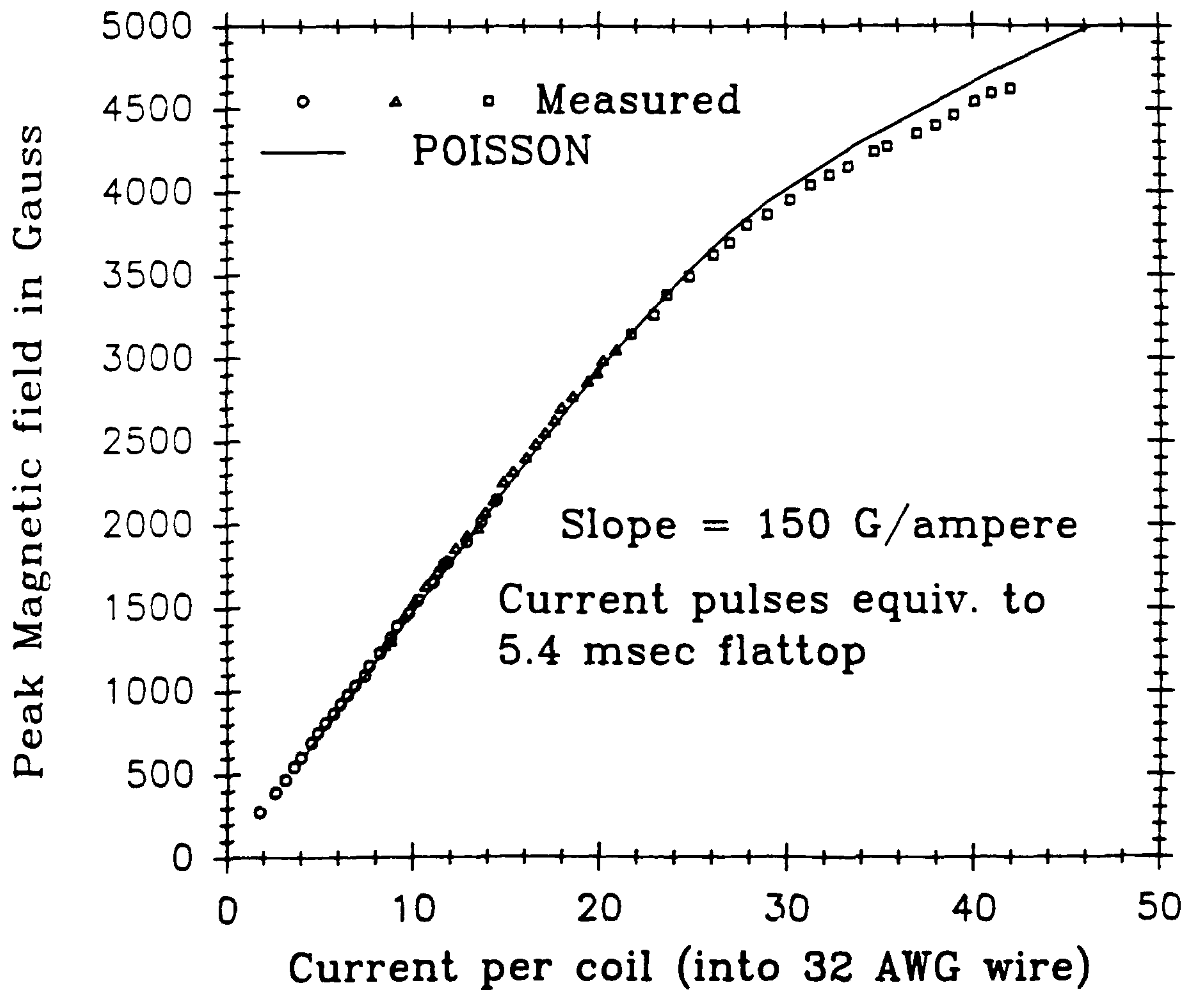
Fig. 1 Stoner,Chen,Bekefi

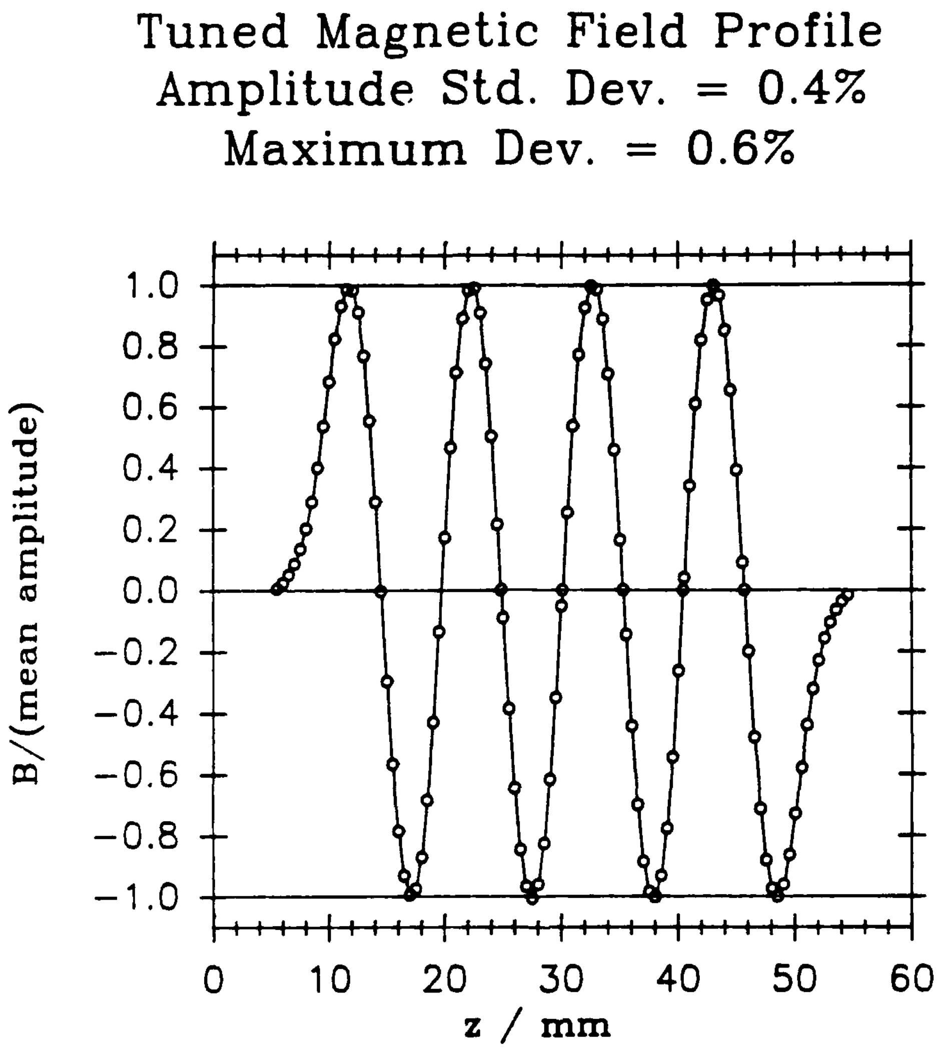


MW–3 MAGNETIC FLUX MAP (computed, POISSON)

On-Axis Peak Field vs. Current

MIT Microwiggler Prototype

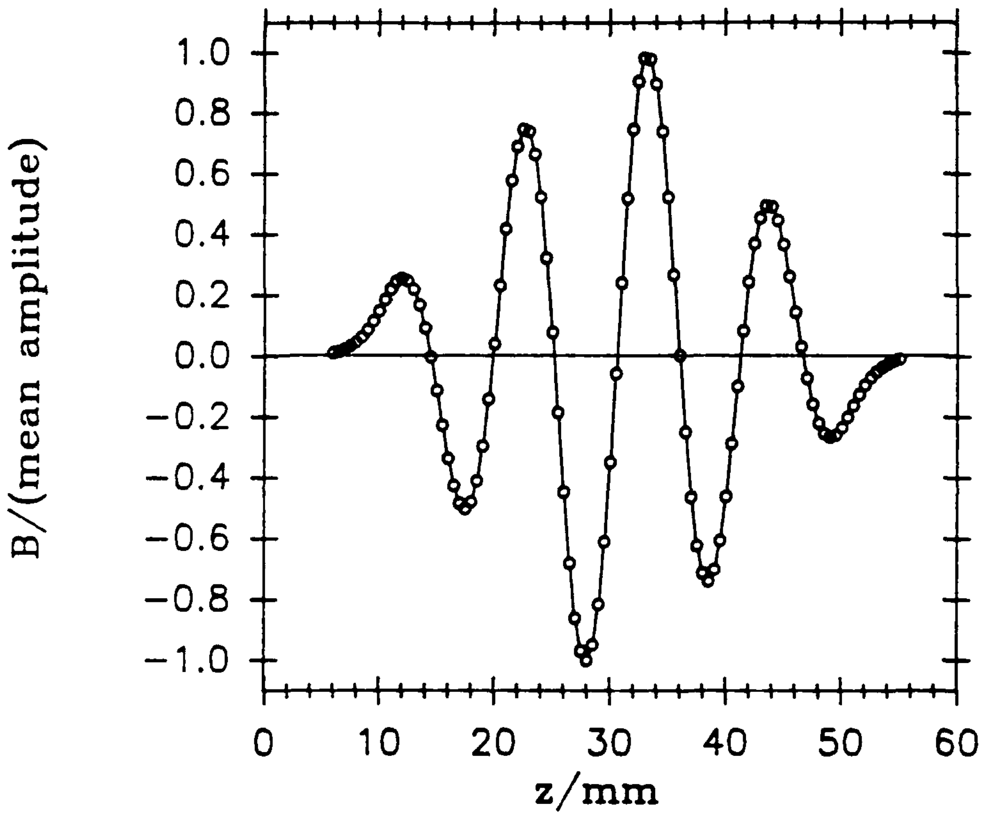




Measured Wiggler Field: On–Axis Profile

- **Peak Amplitudes were tuned to a constant value**
- **Standard deviation from the mean: 0.4%**
- **Maximum deviation from the mean: 0.6%**
- **With improved potentiometers, a maximum deviation of 0.2% will be readily attainable**

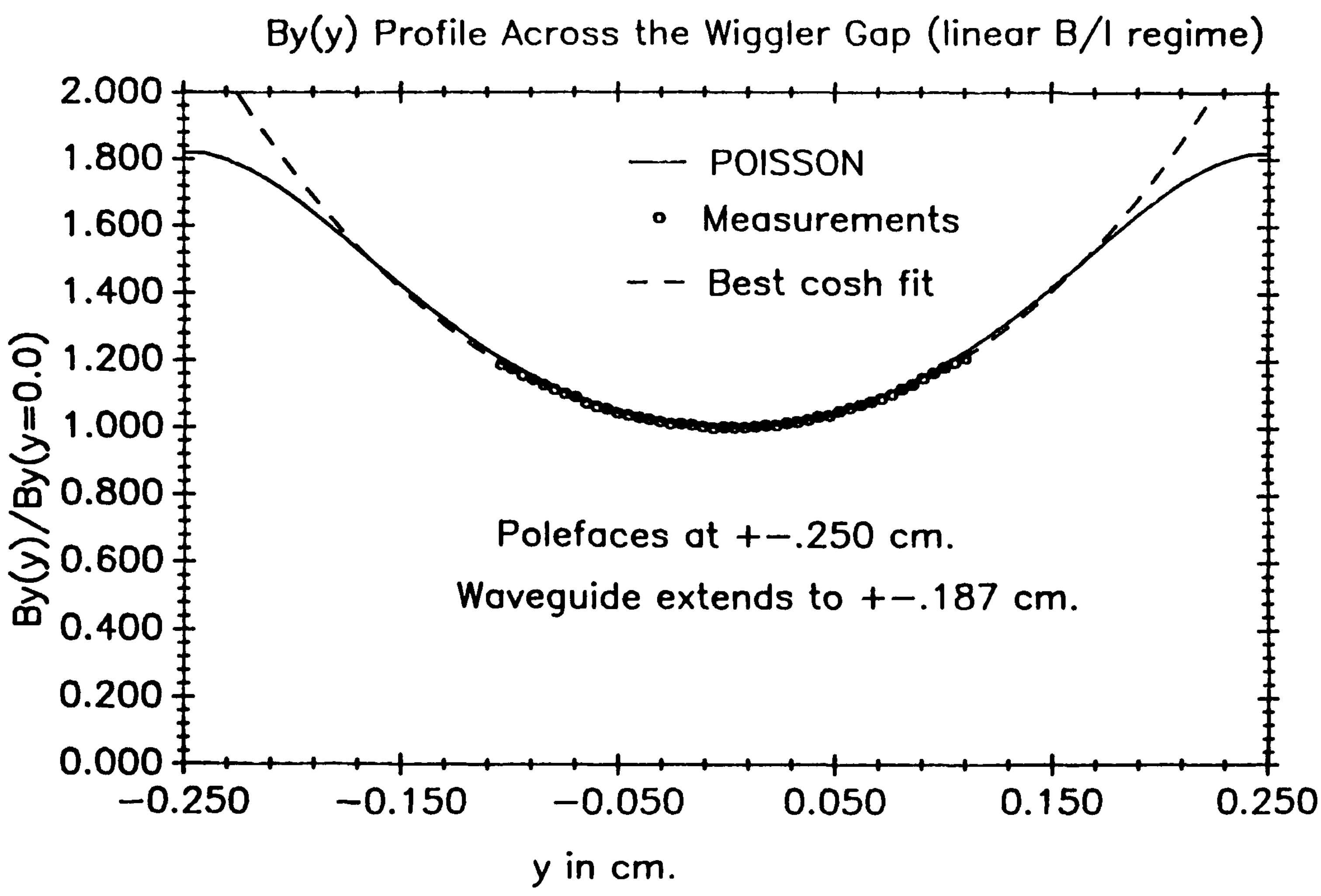
Tuned Magnetic Field Profile
Linear Ramp



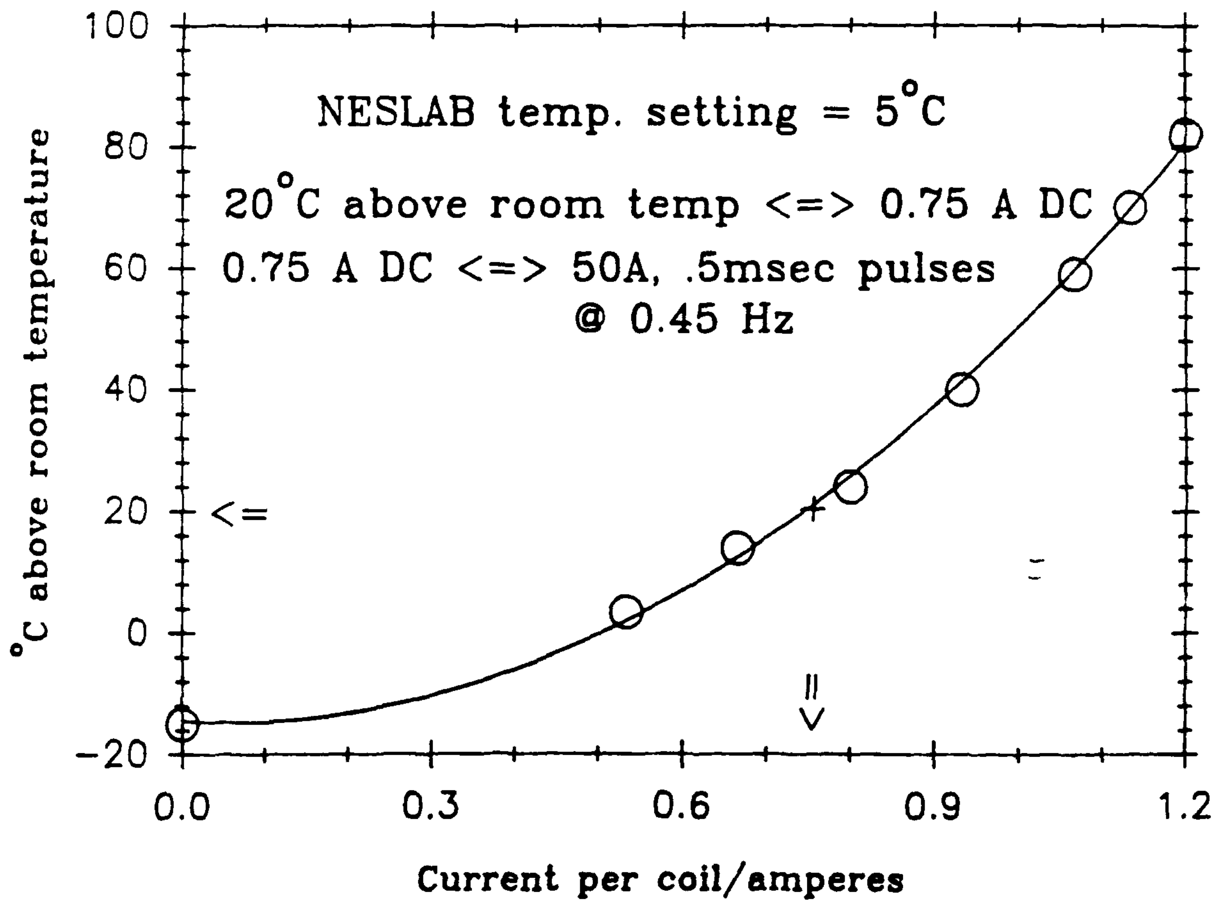
Measured Wiggler Field: On–Axis Profile

- o **Peak amplitudes were tuned to a 'linear ramp' profile (peak amplitude ratios of 0.25:0.5:0.75:1.0)**

- o **Proves that high–precision adiabatic up–tapering or down–tapering can be implemented with a wiggler of this design**

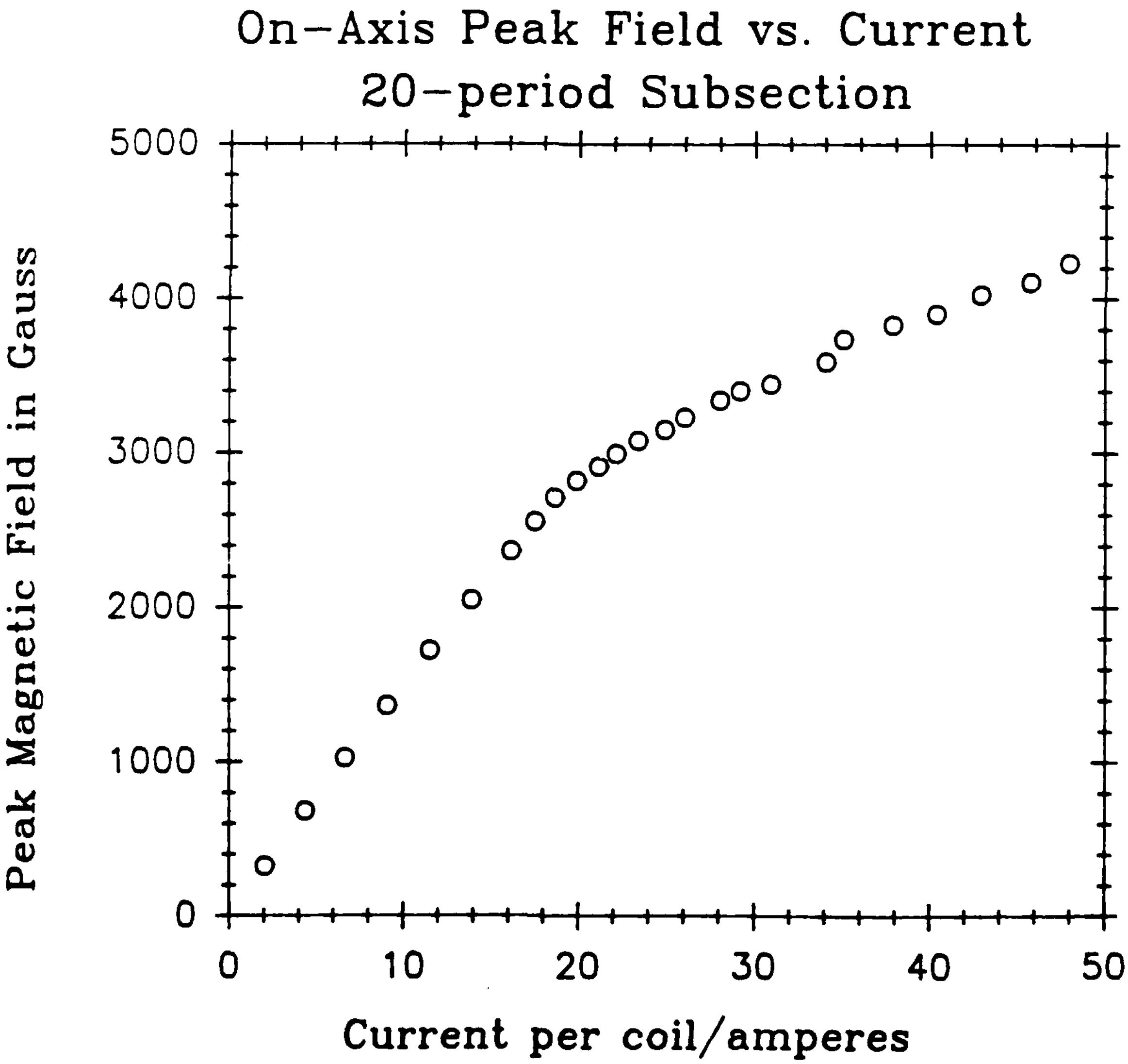

By(y) Profile Across the Wiggler Gap (linear B/I regime)
By(y)/By(y=0.0)
2.000
1.800
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
−0.250
−0.150
−0.050
0.050
0.150
0.250
y in cm.
POISSON
Measurements
Best cosh fit
Polefaces at +−.250 cm.
Waveguide extends to +−.187 cm.

Coil Temperature as a Function of Coil Current

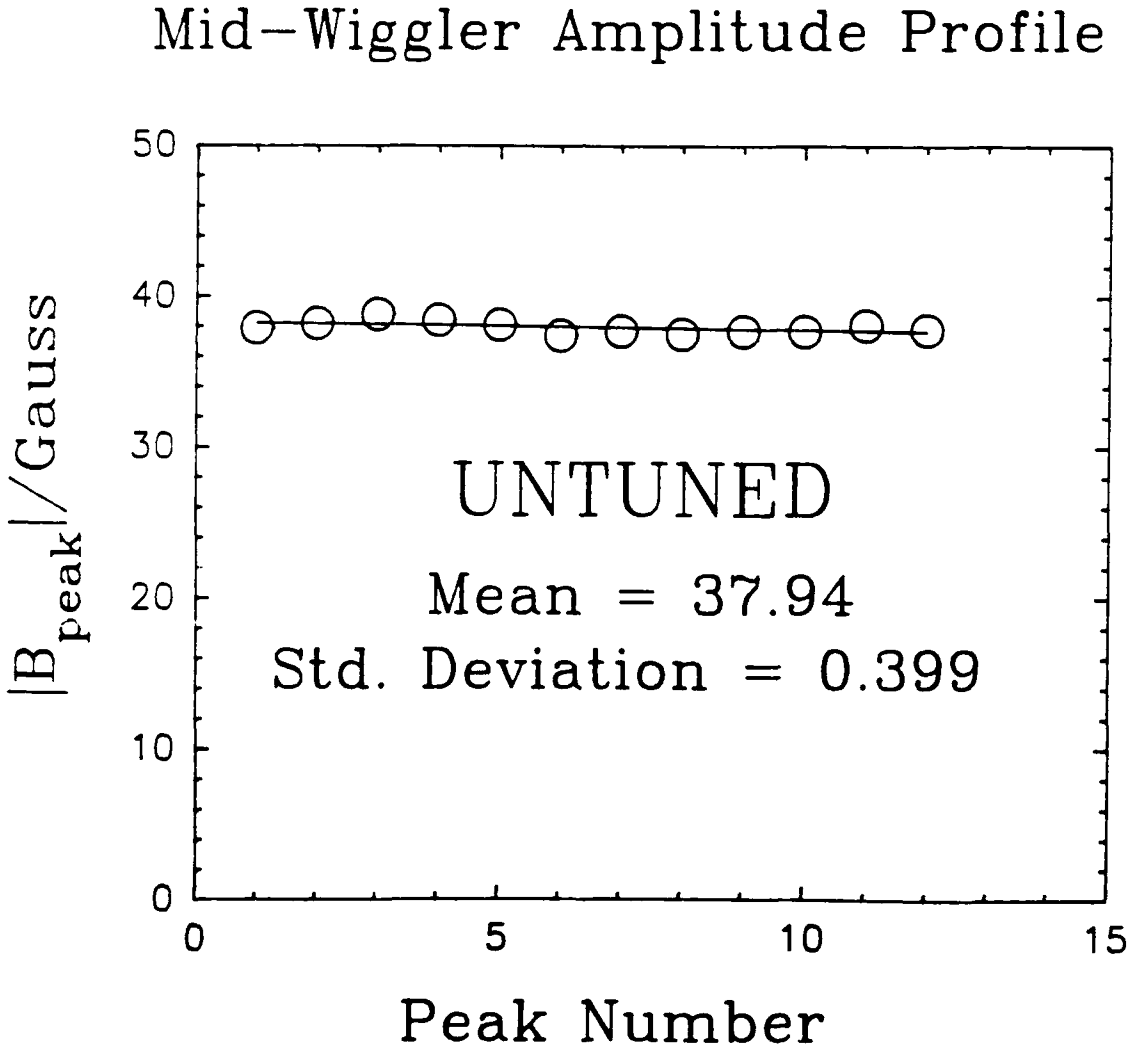


MIT Microwiggler

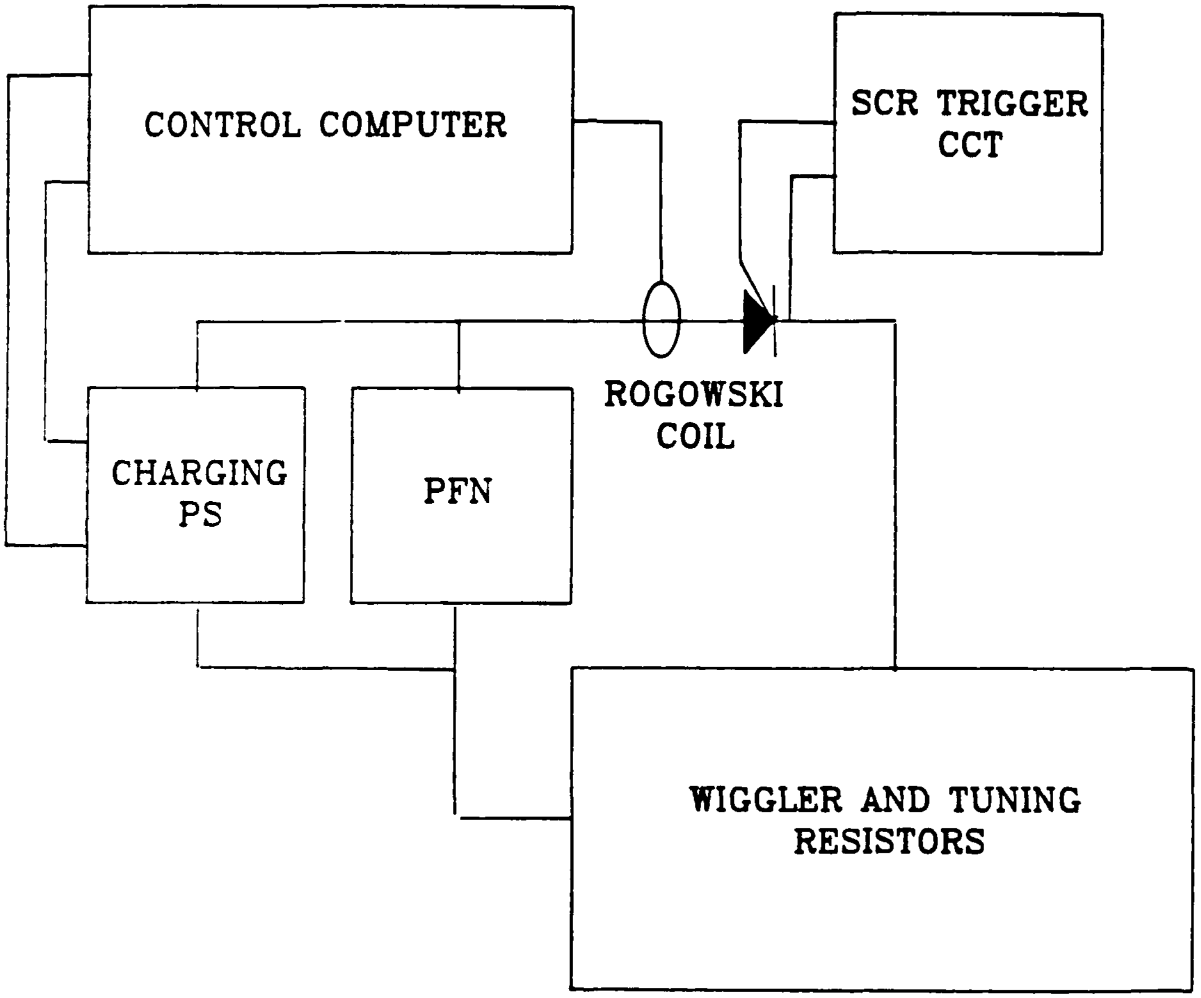
$\lambda_w = 8.8$ mm, G = 4.4 mm
70 periods



MIT Microwiggler



MICROWIGGLER PULSER



- o Maximum Peak Current = 20 kA
- o Shot-to-Shot Stability ~ 0.1% RMS
- o Rep-rate ~ 0.3 Hz
- o Max. Voltage = 600 V.

MIT/BNL MICROWIGGLER FEL COLLABORATION IS CURRENTLY UNDER CONSTRUCTION

- e-beam (BNL ATF):
  0.3 mm radius, $\Delta\gamma/\gamma < .001$
  Normalized emittance ~6 mm-mrad
  50 A, 6 psec micropulses, 100 per 1 μsec macropulse, at 50 MV
  SLAC-style RF linac with photocathode

- Wiggler (MIT):
  8.8 mm period, 70 periods, each half-period tunable
  4.4 mm gap, planar geometry
  Uniform axial field profile, ends tapered for zero displacement and steering
  Operating magnetic field level $\geq$5 kG
  Tuneable to accuracy of $\leq$0.5%

- Output radiation:
  532 nm
  100 MW intracavity power, 10% out-coupling: 10 MW peak output

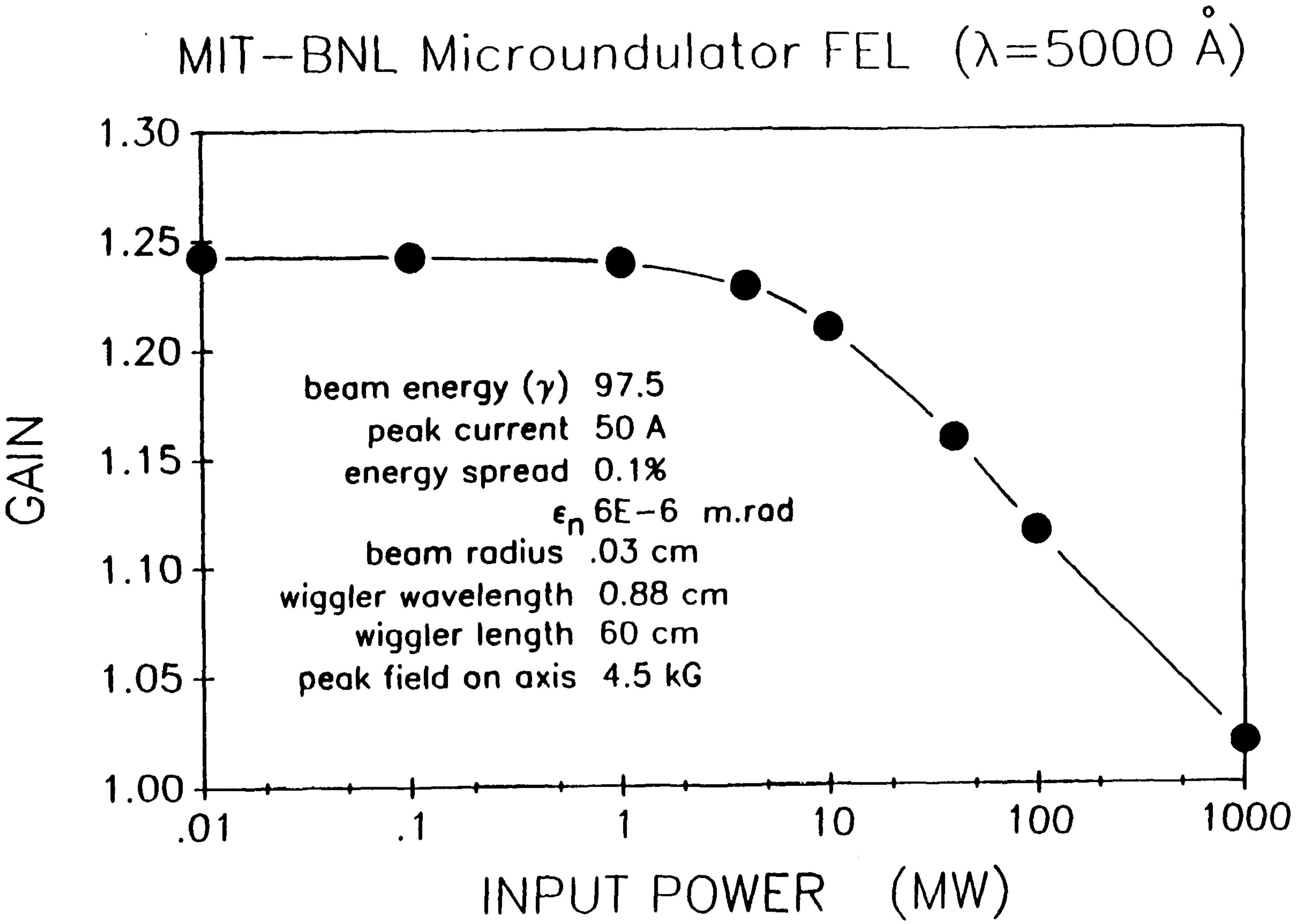

MIT–BNL Microundulator FEL (λ=5000 Å)
GAIN
1.30
1.25
1.20
1.15
1.10
1.05
1.00
beam energy (γ) 97.5
peak current 50 A
energy spread 0.1%
εn 6E–6 m.rad
beam radius .03 cm
wiggler wavelength 0.88 cm
wiggler length 60 cm
peak field on axis 4.5 kG
.01
.1
1
10
100
1000
INPUT POWER (MW)

Figure 9

CONCLUSIONS

- The MIT microwiggler prototype produced on-axis magnetic fields of nearly 5 kG. Tuning was used to reduce random and systematic wiggler errors to $\leq$ 0.5%. Temperature measurements show that 0.5 msec, 5 kG pulses can be produced at 1 Hz at an operating temperature of 40 ^{o}C above room temperature.

- We are collaborating with the Brookhaven National Laboratory to develop a λ = 532 nm FEL using a 70-period microwiggler and a 50 MeV RF LINAC. Preliminary simulations show that oscillator operation is attainable.

- We have made preliminary measurements of a 20-period subsection of the MIT microwiggler. Saturation characteristics are acceptable and field uniformity without tuning is around 1% RMS.

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